

Example 4d: Internal Loading Options for Laminate

This example problem demonstrates how to invoke the various internal mechanical loading options available for a laminate in MAC/GMC 4.0. In particular, the laminate analyzed is the identical quasi-isotropic 0.25 fiber volume fraction SiC/Ti-21S laminate presented in Example 3h. Because of the plane stress assumption inherent in lamination theory, only loading in the x-y plane of the laminate is permissible (where the z-direction is the through-thickness direction of the laminate, [Figure 1.2](#)). Further, loading in the form of midplane curvatures and moment resultants (in addition to midplane strains and force resultants) may be applied to the laminate using the internal loading option 4 – 6. Thus, the meaning of the various loading options is different in the case of a laminate as compared to the repeating unit cell analysis. For details, see Section 4 of the Keywords Manual. In the present example, the loading option is successively increased from 1 to 6 to apply the three midplane strain components and the three midplane curvatures in separate executions of the code.

MAC/GMC Input File: `example_4d.mac`

```
Lamination theory - Internal loading options for laminates
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*LAMINATE
  NLY=7
  LY=1 MOD=2 THK=0.125 ANG=90  ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=2 MOD=2 THK=0.125 ANG=45  ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=3 MOD=2 THK=0.125 ANG=0   ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=4 MOD=2 THK=0.25 ANG=-45  ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=5 MOD=2 THK=0.125 ANG=0   ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=6 MOD=2 THK=0.125 ANG=45  ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=7 MOD=2 THK=0.125 ANG=90  ARCHID=6 R=1. VF=0.25 F=1 M=2
*MECH
# -- Alter LOP from 1 - 6 to generate example problem results
  LOP=1
  NPT=2 TI=0.,200. MAG=0.,0.02 MODE=1
*THERM
  NPT=2 TI=0.,200. TEMP=650.,650.
*SOLVER
  METHOD=1 NPT=2 TI=0.,200. STP=1.
*PRINT
  NPL=6
*XYPLOT
  FREQ=5
  LAMINATE=6
  NAME=example_4d_exx X=1 Y=10
  NAME=example_4d_eyy X=2 Y=11
  NAME=example_4d_exy X=6 Y=12
  NAME=example_4d_kxx X=7 Y=13
  NAME=example_4d_kyy X=8 Y=14
  NAME=example_4d_kxy X=9 Y=15
  MACRO=0
  MICRO=0
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:

Number of materials:	2	(NMATS=2)
Materials:	SiC fiber	(MATID=E)
	Ti-21S	(MATID=A)

Constitutive models:	SiC fiber: linearly elastic	(CMOD=6)
	Ti-21S matrix: Isotropic GVIPS	(CMOD=4)

3) Analysis type (***LAMINATE**) → Laminate Analysis [KM_3]:

Number of layers: 7 (NLY=7)

Layer	Analysis Model	Thickness	Fiber Angle	Architecture	Aspect Ratio	Volume fraction	Fiber material	Matrix material
(LY=)	(MOD=2)	(THK=)	(ANG=)	(ARCHID=6)	(R=1.)	(VF=0.25)	(F=1)	(M=2)
1	GMC-2D	0.125	90°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S
2	GMC-2D	0.125	45°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S
3	GMC-2D	0.125	0°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S
4	GMC-2D	0.25	-45°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S
5	GMC-2D	0.125	0°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S
6	GMC-2D	0.125	45°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S
7	GMC-2D	0.125	90°	7x7 circle, rect. pack	1.	0.25	SiC	Ti-21S

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	1 – 6	(LOP=1 through LOP=6)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0., 200.)
Load magnitude:	0., 0.02	(MAG=0., 0.02)
Loading mode:	midplane strain/curvature control	(MODE=1)

☞ Note: To generate the results presented in this example, the loading option (LOP) must be changed from 1 to 6, successively.

b) Thermal (***THERM**) [KM_4]:

Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0., 200.)
Temperature points:	650., 650. °C	(TEMP=650., 650.)

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0., 200.)
Time step sizes:	1. sec.	(STP=1.)

5) Damage and Failure: None

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)
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b) x-y plots (***XYPLOT**) [KM_6]:

Frequency:	5	(FREQ=5)
Number of laminate plots:	6	(LAMINATE=6)
Laminate plot name:	example_4d_exx example_4d_eyy example_4d_exy example_4d_kxx example_4d_kyy example_4d_kxy	(NAME=example_4d_exx) (NAME=example_4d_eyy) (NAME=example_4d_exy) (NAME=example_4d_kxx) (NAME=example_4d_kyy) (NAME=example_4d_kxy)
Laminate plot x-y quantities:	ϵ_{xx}^0, N_{xx} ϵ_{yy}^0, N_{yy} ϵ_{xy}^0, N_{xy} K_{xx}, M_{xx} K_{yy}, M_{xy} K_{xy}, M_{xy}	(X=1 Y=10) (X=2 Y=11) (X=6 Y=12) (X=7 Y=13) (X=8 Y=14) (X=9 Y=15)
Number of macro plots:	0	(MACRO=0)
Number of micro plots:	0	(MICRO=0)

7) End of file keyword: (***END**)

Results

Figure 4.7 shows the response of the quasi-isotropic laminate to the three applied midplane strain components ($LOP=1-3$), whereas Figure 4.8 shows the laminate response to the three applied curvature components ($LOP=4-6$). It is clear from Figure 4.7 that the extensional behavior of the laminate is isotropic while Figure 4.8 shows that the bending behavior is anisotropic. The response of the laminate to the applied K_{yy} is stiffer than that to the applied K_{xx} because the outer plies of the laminate (which are farthest from the midplane and therefore contribute more to the bending stiffness) are oriented along the y-axis. It should also be noted that this laminate exhibits normal-shear coupling in its bending response (see Table 3.1).

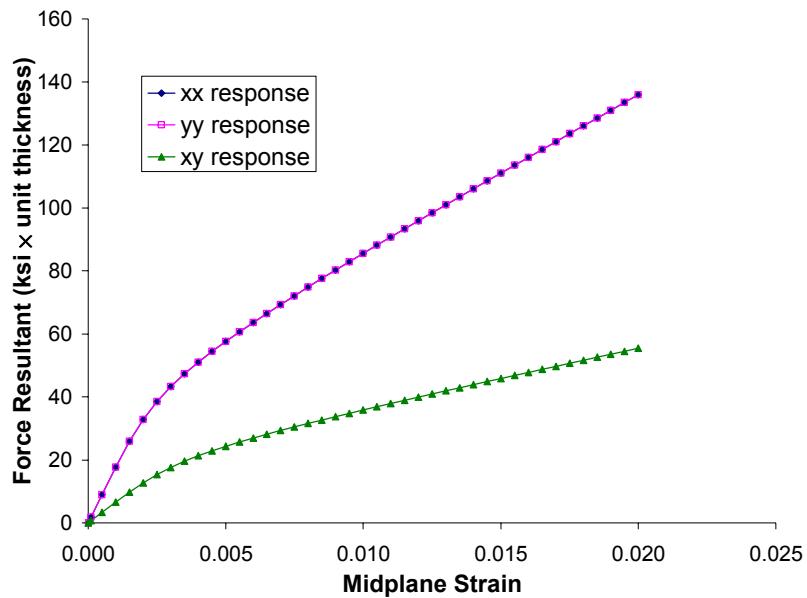


Figure 4.7 Example 4d: $N_{ij} - \varepsilon_{ij}^0$ response of a 0.25 fiber volume fraction quasi-isotropic SiC/Ti-21S laminate to applied midplane strains at 650 °C.

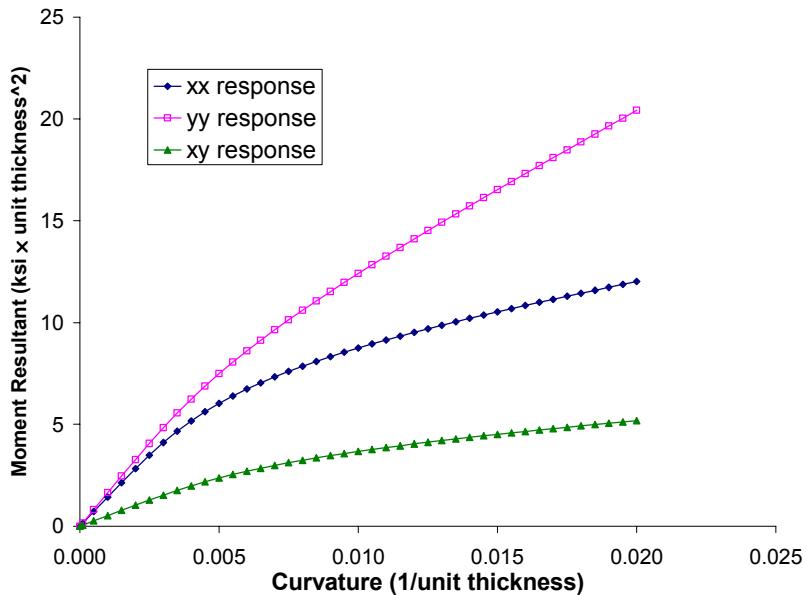


Figure 4.8 Example 4d: $M_{ij} - \kappa_{ij}$ response of a 0.25 fiber volume fraction quasi-isotropic SiC/Ti-21S laminate to applied curvatures at 650 °C.